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FORCES AND MOMENTS DUE TO AIR JETS EXHAUSTING PARALLEL TO LARGE FLAT PLATES IN A NEAR VACUUM

by Joseph J. Janos and Sherwood Hoffman

Langley Research Center
Langley Station, Hampton, Va.

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FORCES AND MOMENTS DUE TO AIR JETS EXHAUSTING PARALLEL TO LARGE FLAT PLATES IN A NEAR VACUUM

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SUMMARY

An investigation was conducted in the 41-foot-diameter (12.5-meter) vacuum sphere at the Langley Research Center to determine the impingement forces, moments, and centers of pressure caused by air jets exhausting parallel to flat plates. Three flat plates of equal length but with width-length ratios of 0.25, 0.50, and 1.0 were tested. The nozzles used were conical and had nominal exit Mach numbers of 1.0, 3.0, and 5.0. The locations of the nozzles were varied longitudinally and vertically. The plate widths were 48, 96, and 192 throat diameters. The ratios of total pressure to ambient pressure varied from 22×10^6 to 15.5×10^6, and the ratios of jet exit pressure to ambient pressure varied from 11.6×10^6 to 3.2×10^5. The pressure altitude was 312 000 feet (95 km).

The impingement forces, moments, and center-of-pressure trends were similar for all three plates. The magnitudes of the impingement parameters were decreased by reducing the plate width or effective plate length, raising the nozzle location, increasing the exit Mach number, or decreasing the jet-flow turning angle. For the nozzle positions surveyed, the normal force on the plate was as high as 47.5 percent of the thrust for a nozzle close to the widest plate and as low as 4.8 percent of the thrust for a nozzle relatively high above the narrowest plate.

INTRODUCTION

One of the important problems associated with the operation of jets in space or in the upper atmosphere is the interference forces caused by the expanding jets. The jets expand to the limits of their turning angles and may impinge upon any nearby surface area. Since this flow is quite complex and analytical solutions are difficult, an experimental program has been undertaken to measure the impingement forces and moments directly. In reference 1 the interference effects were determined for a flat plate mounted on a balance in a vacuum sphere. Nozzle vertical position, nozzle longitudinal position, exit Mach number, jet-flow turning angle, and flat-plate incidence angle were investigated for air. The data for a square plate in reference 1 are essentially those for a wide plate of various

finite or effective lengths. The present test program was undertaken in order to determine the effect of plate width on the interference forces and moments from the small control jet-air nozzles.

The results for three plate widths are compared in this paper. The data for the widest plate are from reference 1, and the other data are for plates that were constructed to have one-half and one-quarter the width of the widest plate. Air jets exhausting parallel to the plates were utilized for nozzles having nominal exit Mach numbers of 1.0, 3.0, and 5.0. The ratios of total pressure to ambient pressure, which were the same as those of reference 1, varied from about 15.5×10^6 to 22×10^6 at a pressure altitude of approximately 312 000 feet (95 km) in the 41-foot-diameter (12.5-meter) vacuum sphere at the Langley Research Center.

SYMBOLS

The axis system, dimension nomenclature, and force relationships are illustrated in figure 1.

d_j diameter of nozzle exit

d_t diameter of nozzle throat

F_X force on flat plate parallel to surface

F_Z force on flat plate normal to surface

H normal distance from plate to center of nozzle exit

L total length of plate

ΔL distance along plate between the trailing edge and the intersection of normal reference line from plate to nozzle exit

M_j nozzle exit Mach number

M_n pitching moment of plate referred to nozzle exit center line

p_a ambient pressure in vacuum sphere

p_j nozzle exit static pressure

T_j gross thrust of nozzle

W total width of plate

x_b, z_b coordinates referred to balance

x_{cp} center-of-pressure location measured from center of nozzle exit

α_n initial jet turning angle measured between nozzle center line and tangent to jet boundary at nozzle lip

θ_n nozzle half-angle

APPARATUS

The apparatus consisted of a three-component balance, a dashpot, a test stand, three nozzles, a plenum chamber pressure gage, and two flat plates, as illustrated in figures 1 and 2. The two flat plates were modeled from the smooth 24-inch-square (61-cm) plate of reference 1, for which data are also presented herein. All the plates had lengths of 24 inches (61 cm), but the two flat plates constructed to have one-half and one-fourth the width of the basic plate of reference 1 had widths of 12 inches (30.5 cm) and 6 inches (15.24 cm), respectively. The three plate widths can also be expressed as 192, 96, and 48 throat diameters. Static loadings of each plate (greater than the anticipated maximum loading due to jet impingement) produced no measurable deflections and thus the plates could be considered as rigid for the tests. A small rectangular aluminum block was attached to the geometric center of the bottom of each test-plate structure for mounting the balance. Attached to the test stand was a dashpot to dampen the amplitude of the oscillations induced on the test plate by the jet impingement.

Each nozzle tested was mounted on a fixed-position stand which was separated from the rest of the test setup as shown in figure 2. Each test plate was adjustable relative to the nozzle in both longitudinal and vertical translation by a remotely controlled test stand. Air from a tank farm pressurized at 1.73×10^5 lb/ft^2 abs $\left(8.3 \times 10^6 \text{ N/m}^2 \text{ abs}\right)$ was fed into an accumulator. The air supply from the accumulator to the nozzles located in the center of the 41-foot-diameter (12.5-meter) vacuum sphere was controlled by means of a pressure regulator and a quick opening valve. This arrangement enabled an accurate control of the chamber pressure to be maintained for each test run. The range of chamber pressures for the different nozzles varied from 21.5×10^3 lbf/ft^2 abs $\left(10.3 \times 10^5 \text{ N/m}^2 \text{ abs}\right)$ to 30.7×10^3 lbf/ft^2 abs $\left(14.7 \times 10^5 \text{ N/m}^2 \text{ abs}\right)$.

TESTS AND MEASUREMENTS

The tests were conducted in the 41-foot-diameter (12.5-meter) vacuum sphere at the Langley Research Center at an ambient pressure of 0.0014 lbf/ft^2 (0.067 N/m^2) which corresponds to a pressure altitude, based on the 1962 U.S. Standard Atmosphere, of about 312 000 feet (95 km). The ratios of total pressure to ambient pressure were 22×10^6, 17×10^6, and 15.5×10^6 for the Mach number 1.0, 3.0, and 5.0 nozzles, respectively. The corresponding ratios of jet exit pressure to ambient pressure were 1.2×10^7, 4.9×10^6, and 3.2×10^5 and are presented in figure 3.

The balance measured normal force and pitching moment. A sample oscillograph record is presented in figure 4 to show the traces of the normal force, pitching moment, and chamber pressures for a typical test run. The running time for each test was about 25 msec. The data point read was a faired value on the oscillographic trace over a 5-msec interval preceding air supply cutoff, as shown in figure 4. Calculations of the ambient pressure during the relatively short run time, based on the limiting velocity of the jet and vacuum sphere size, showed that the local pressure altitude of about 312 000 feet (95 km) would not change during this test interval. In general, the measurement accuracy was estimated to be within ± 2 percent of the full-scale ranges of the quantities measured by the balance. Tests were conducted with the air from which approximately 95 percent of the moisture had been removed. Conical nozzles designed to have nominal (isentropic) exit Mach numbers of 1.0, 3.0, and 5.0 were used. All the nozzles tested were conical, had sharp lips, and had approximately the same throat area. The nozzle exit areas were determined from isentropic flow relations to obtain the desired Mach numbers. In order to keep the induced or impingement loads on the plate within the calibrated operating range of the balance, the chamber pressures were adjusted to keep the thrust nearly constant for the systematic runs at approximately 3.19 lbf (14.3 newtons). For the impingement test program the nozzle center line was parallel to the plate and the longitudinal positions were varied at each of six vertical positions. Since the longitudinal travel of the plate was limited, the test series were arranged in overlap at station $\Delta L/L = 0.75$. The minimum vertical nozzle displacement was determined by the maximum diameter of the plenum-chamber—nozzle combination.

The characteristics of all the nozzles tested are summarized in figure 1(c). Both the nominal and one-dimensional theoretical Mach numbers, based on measured throat and exit diameters, are listed in this figure. The stagnation or chamber temperatures were approximately 45° F (280° K). According to reference 2 the Mach number 5.0 air nozzle was operating under saturation temperature and pressures and may have had a 10-percent reduction in exit Mach number due to condensation effects or two-phase flow.

RESULTS AND DISCUSSION

All force data were nondimensionalized by dividing the measured force by the computed gross thrust of each nozzle. Only the normal-force data are presented since the axial-force data were somewhat erratic, with the maximum axial force being only about 5 percent of the thrust for the nozzle position closest to the plate. The moment data were transferred from the balance to the center of the nozzle exit inasmuch as this point was a common reference point for all nozzle interference studies. The moment was nondimensionalized by the product of computed gross thrust and normal distance to the plate. The center-of-pressure ratio x_{cp}/H was measured from the nozzle exit parallel to the plate, as is shown in figure 1(a). Relationships used for computations are given in reference 1.

The variations of normal-force, moment, and center-of-pressure data at constant vertical positions with longitudinal location are presented in figure 5 for $W/L = 0.25$, in figure 6 for $W/L = 0.50$, and in reference 1 for $W/L = 1.0$. In order to determine the effect of plate width on the impingement forces, cross plots of these data for a longitudinal location of $\Delta L/L = 0.75$ were made and are presented in figure 7. A comparison of these variations shows that reducing the plate width did not alter the trends of the impingement or interference forces and moments for the positions surveyed and nozzles used. In general, the largest values of F_Z/T_j, M_n/T_jH, and x_{cp}/H were obtained from the nozzle positions that were closest to the plates. These parameters were reduced by decreasing effective plate length ΔL, decreasing plate width W, increasing nozzle height H, or increasing nozzle exit Mach number. These variables also affect the plate wetted area or jet impingement area and, therefore, the magnitude of the forces and moments. The smallest effective plates tested corresponded to a longitudinal nozzle location $\Delta L/L$ of 0.25; the results in figure 5 show that the forces at this station were relatively large.

Since there are many variables to consider in correlating the data (such as nozzle exit angle, exit Mach number, ratio of specific heats, and ambient (altitude) pressure), the normal-force, moment, and center-of-pressure results were plotted in figure 8 as functions of the estimated initial jet turning angle α_n, which depends upon all these variables. The angle α_n represents an isentropic expansion angle with no corrections for nozzle losses or condensation effects. A longitudinal nozzle location of $\Delta L/L = 0.75$ was selected for the comparison of results from the three plate widths. The comparisons in figure 8 show that the impingement forces and moments are highly dependent on plate width at a given height and turning angle. The largest force ratio F_Z/T_j was obtained for the nozzle position closest to the widest plate ($H/d_t = 8$), with the maximum value being 0.475 at $\alpha_n = 118.5^{\circ}$. The results show that this force ratio can be reduced to

$F_Z/T_j = 0.19$ by changing α_n from 118.5° to 60.5° and W/L from 1.00 to 0.25. The lowest force ratio was obtained for the narrowest plate at the highest nozzle location ($H/d_t = 48$), with the smallest value being 0.048 at $\alpha_n = 60.5°$. The impingement moments and center-of-pressure ratios also decreased (i.e., became less negative) as the plate width was reduced, as is shown in figures 8(b) and 8(c). According to the flat-plate pressure distributions of references 3 and 4 (illustrated in fig. 1(d)), the impingement pressure distribution peaks relatively close to the nozzle exit station and falls off rapidly to a small value. Thus x_{cp}/H should be affected less than F_Z/T_j and M_n/T_jH for the ranges of plate width or effective plate lengths investigated. This result is confirmed by the present test data.

CONCLUDING REMARKS

An investigation was conducted in the 41-foot-diameter (12.5-meter) vacuum sphere at the Langley Research Center to determine the impingement forces, moments, and centers of pressure caused by air jets exhausting parallel to flat plates. Three flat plates of equal length but with width-length ratios of 0.25, 0.50, and 1.0 were tested. The nozzles used were conical and had nominal exit Mach numbers of 1.0, 3.0, and 5.0. The locations of the nozzles were varied longitudinally and vertically.

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Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 27, 1969,
125-19-03-10-23.

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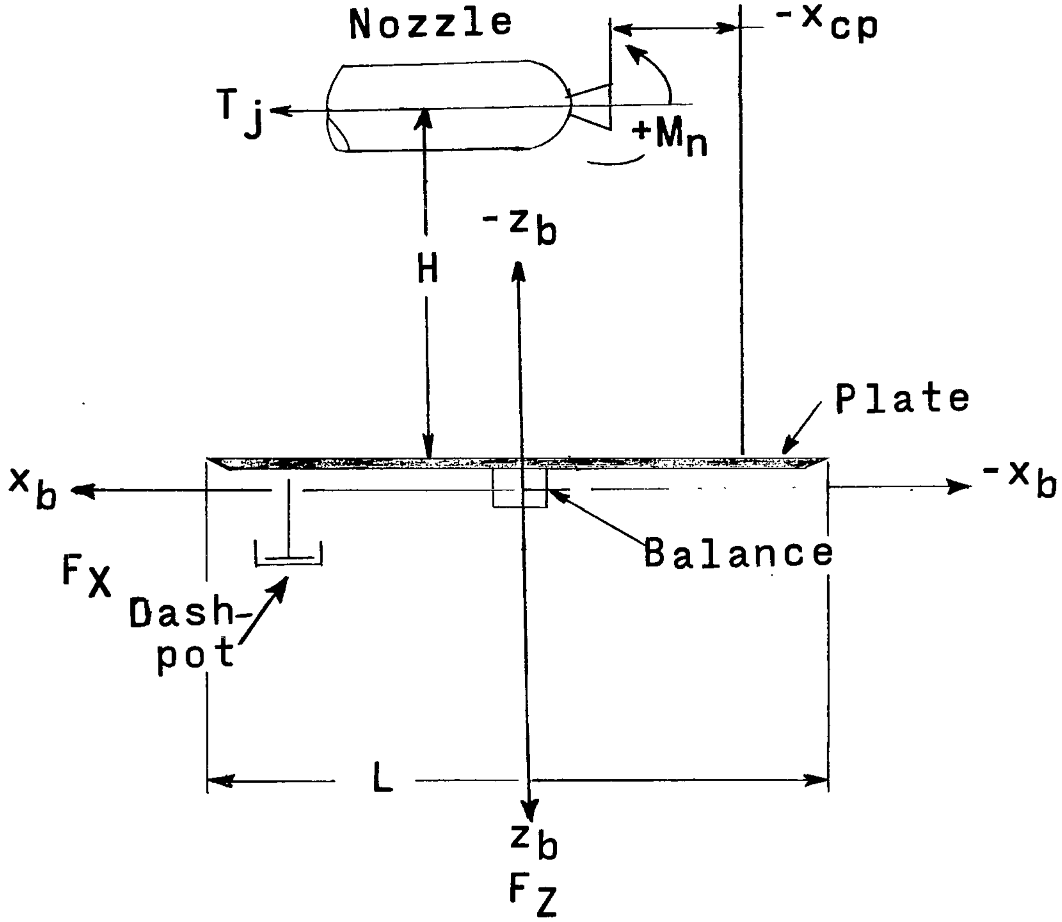
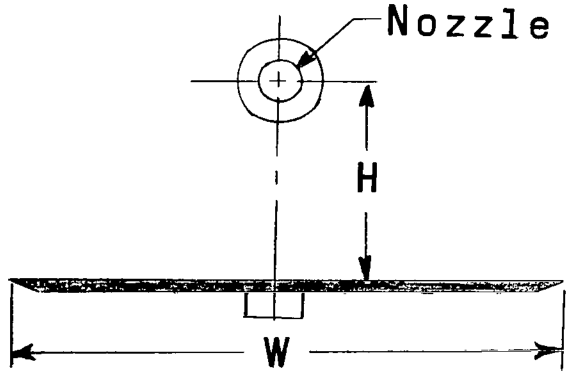
3. Vick, Allen R.; and Andrews, Earl H., Jr.: An Experimental Investigation of Highly Underexpanded Free Jets Impinging Upon a Parallel Flat Surface. NASA TN D-2326, 1964.
4. Vick, Allen R.; Cubbage, James M.; and Andrews, Earl H., Jr.: Rocket Exhaust Plume Problems and Some Recent Related Research. Presented at a Specialist's Meeting on "The Fluid Dynamic Aspects of Space Flight" (Marseille, France), AGARD, Apr. 20-24, 1964.

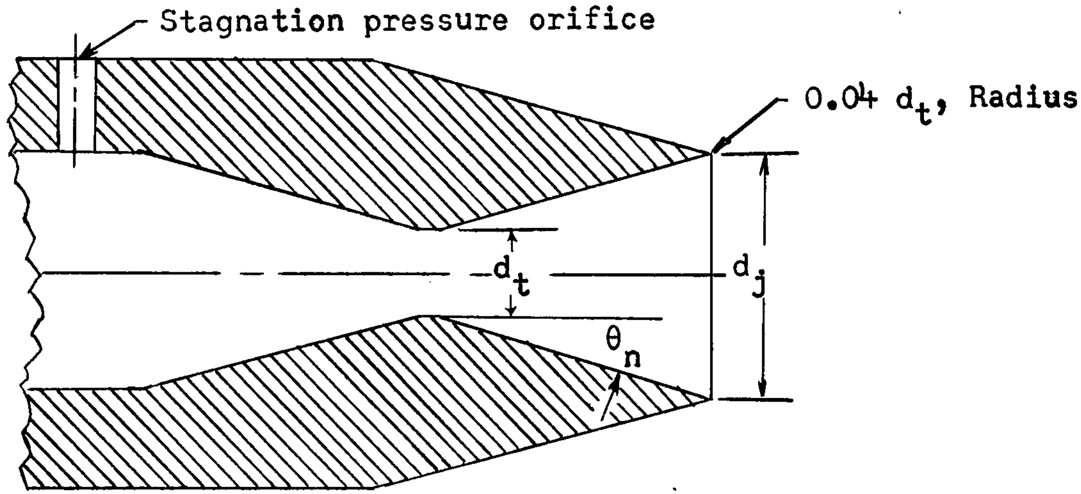


(a) Side view.



(b) Front view.

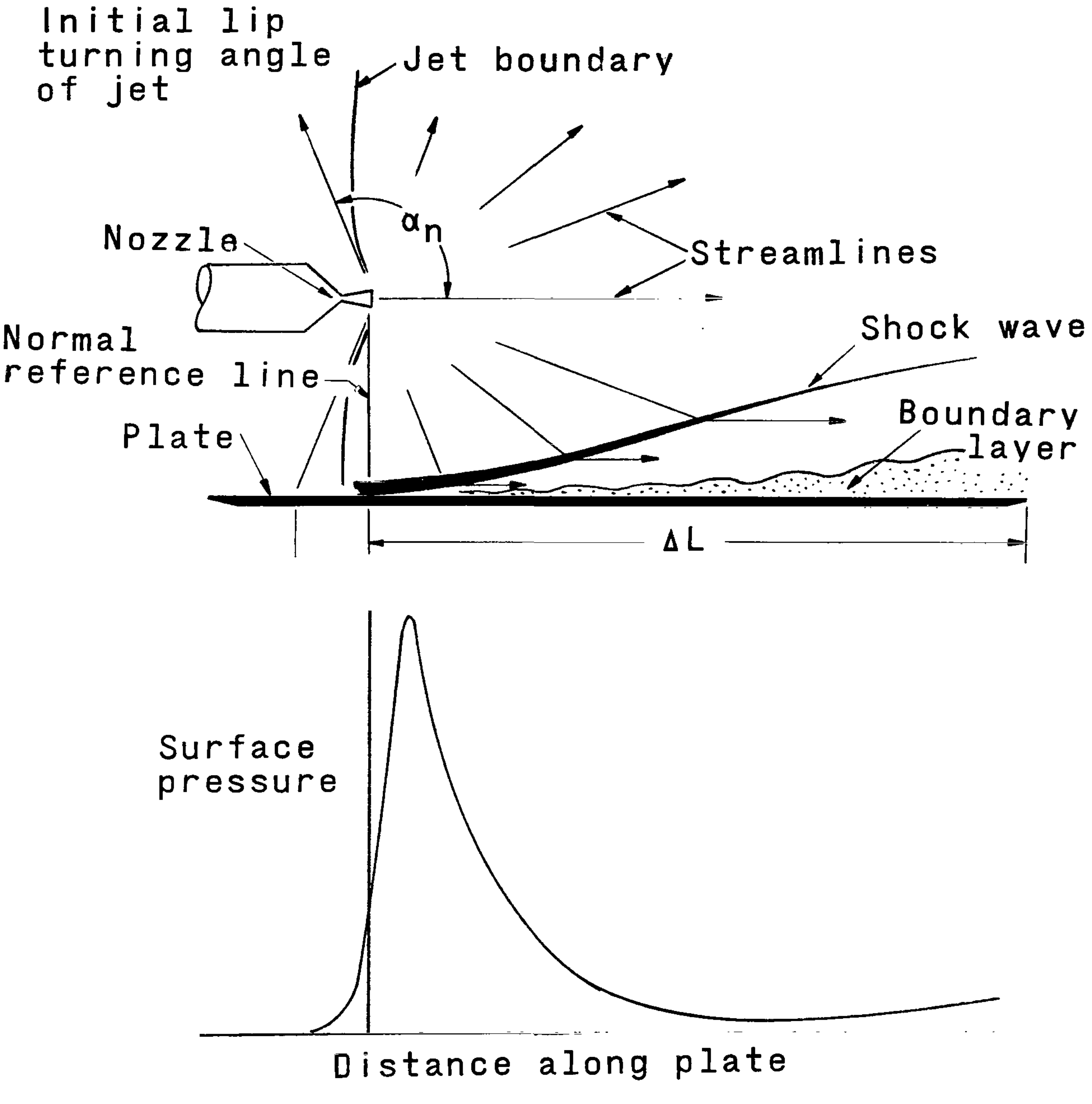
Figure 1.- Schematic representations of apparatus and flow field.



M_j, nominal	M_j, theoretical	d_t		d_j		θ_n, deg	$\frac{p_j}{p_a}$
		in.	cm	in.	cm		
1.0	1	0.125	0.318	0.125	0.318	0	1.2×10^7
3.0	2.96	.125	.318	.252	.640	15	4.9×10^6
5.0	4.92	.129	.327	.625	1.588	15	3.2×10^5

(c) Nozzle characteristics.

Figure 1.- Continued.



(d) Schematic flow field and plate pressures.

Figure 1.- Concluded.

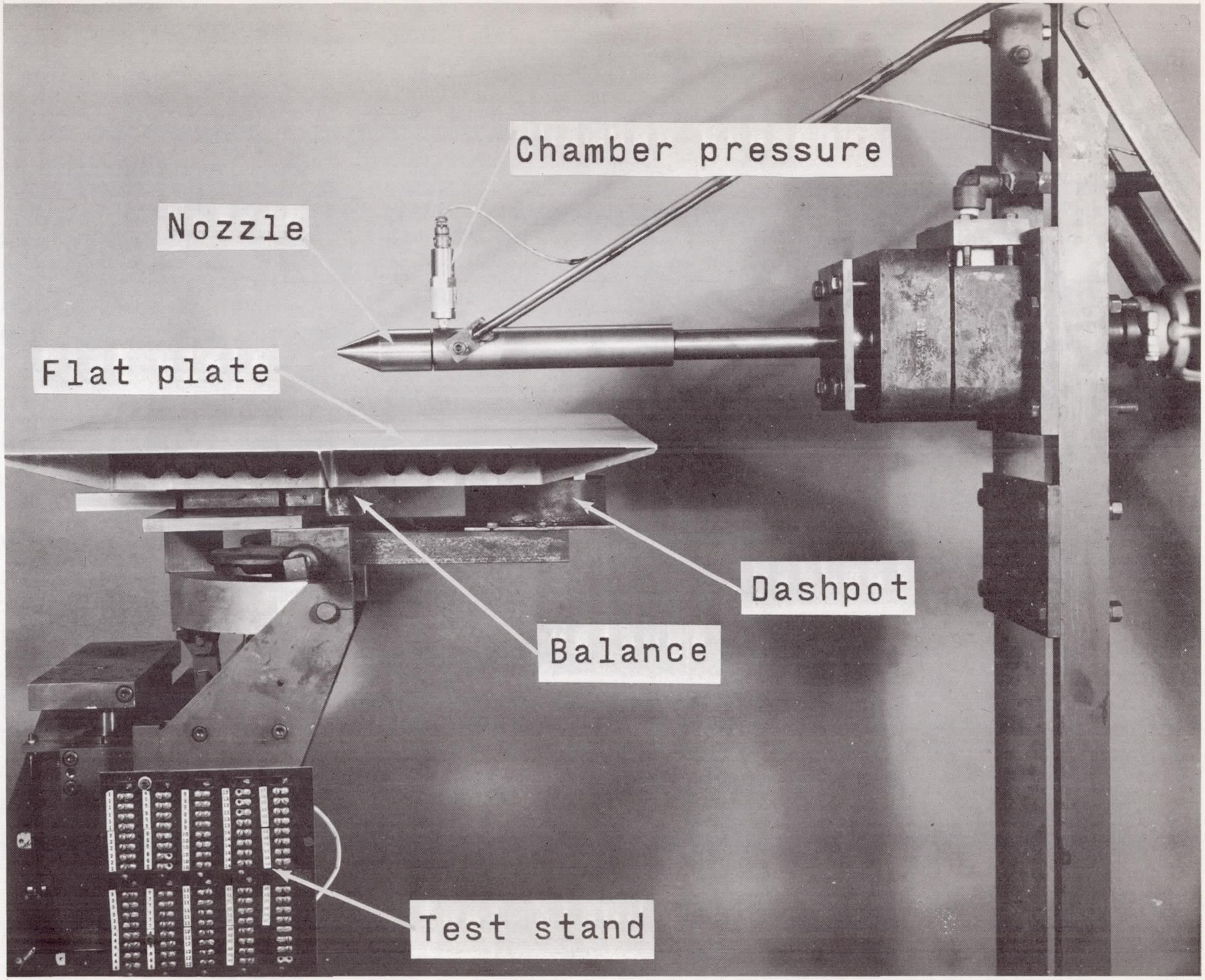


Figure 2.- Photograph of apparatus. L-67-6446.1

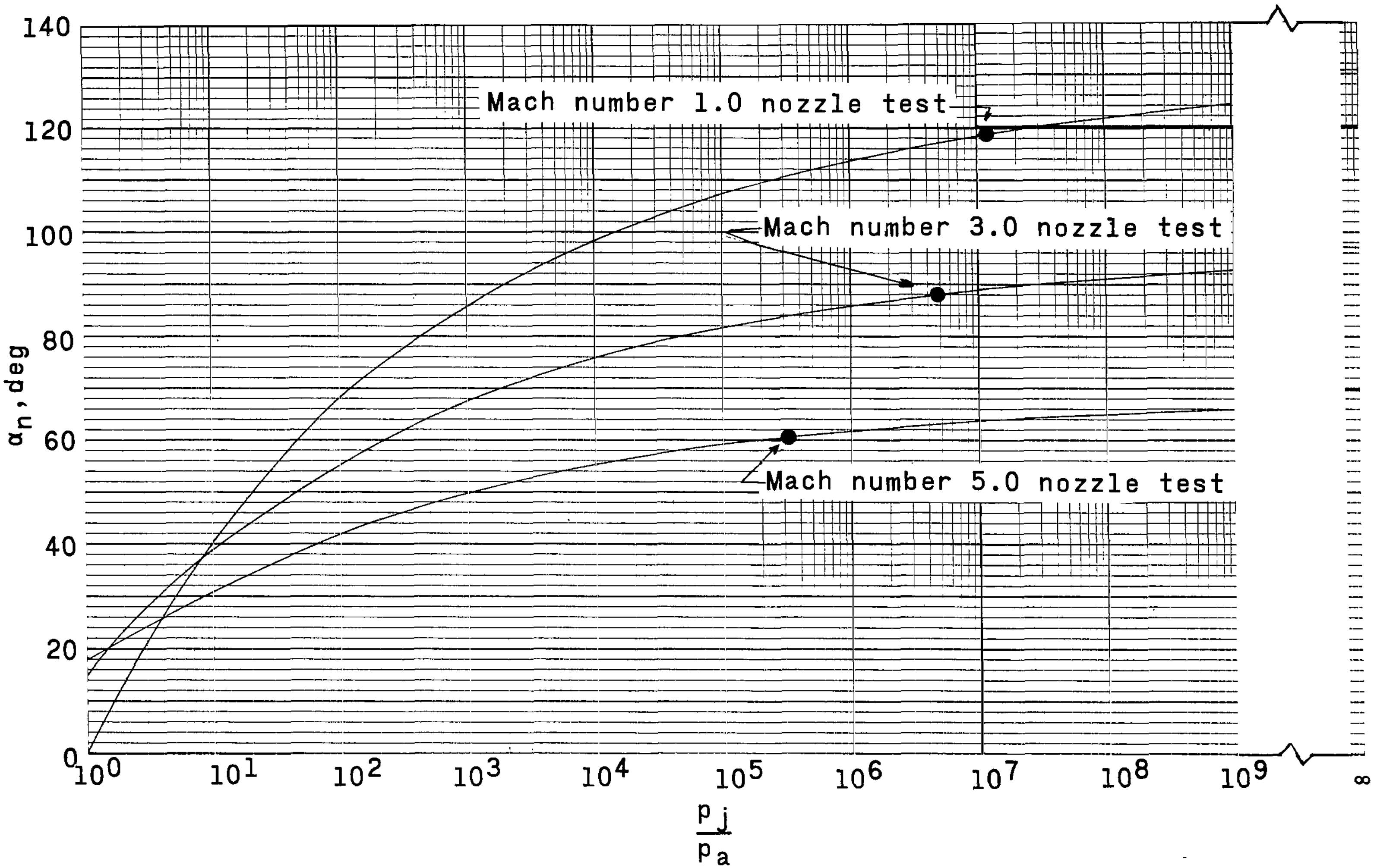


Figure 3.- Variations of the initial turning angle with the ratio of jet exit pressure to ambient pressure for the nozzles.

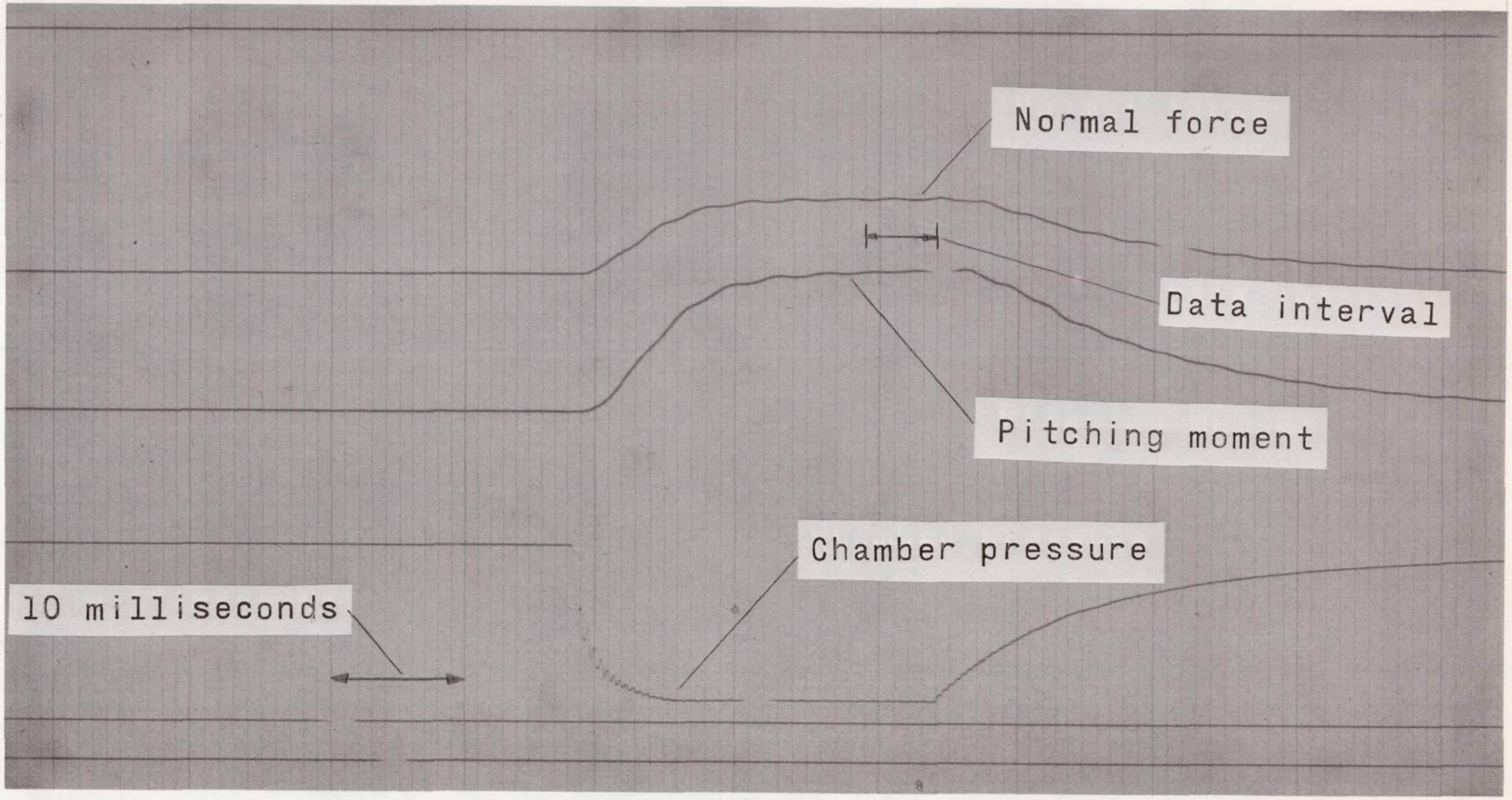
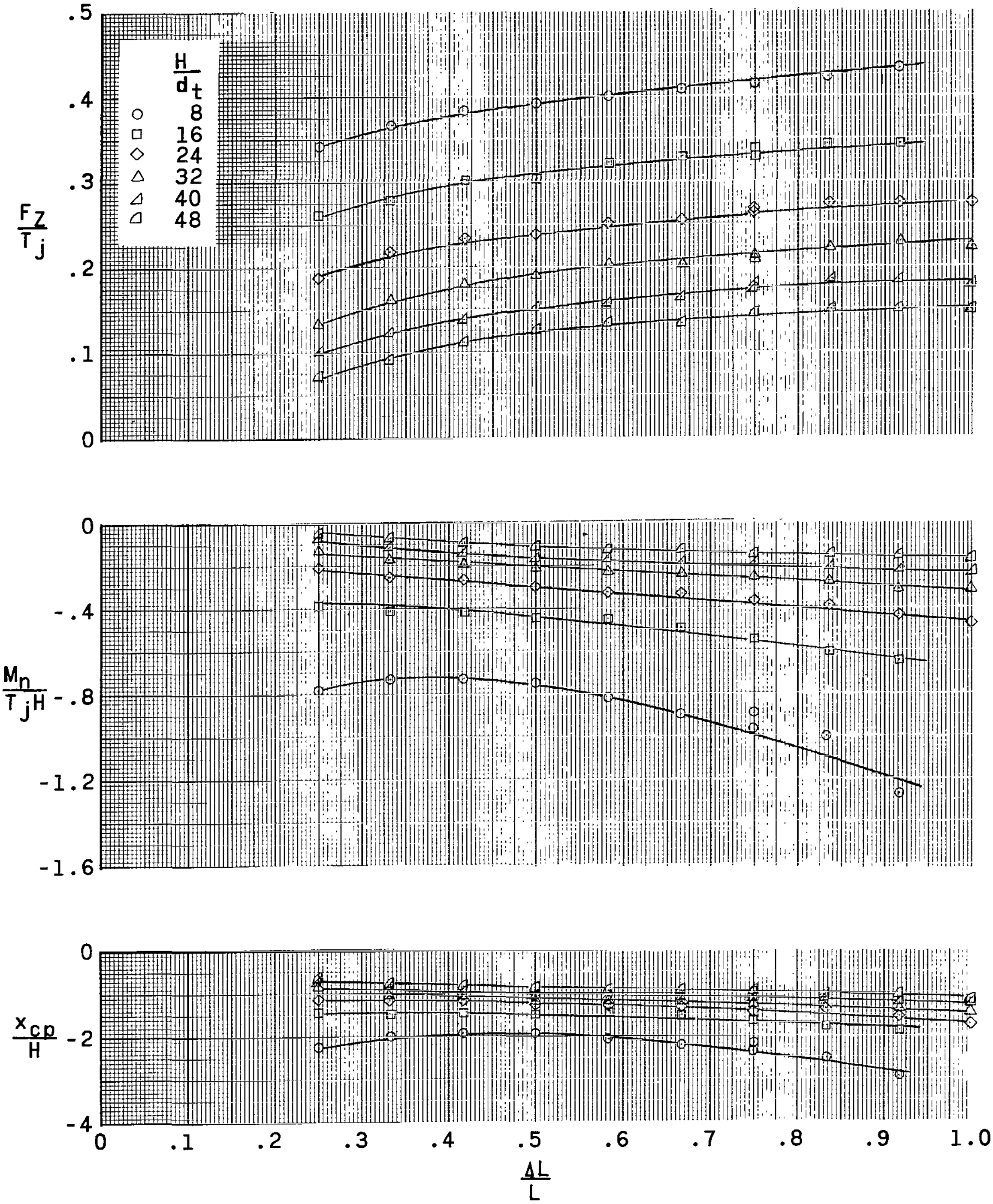
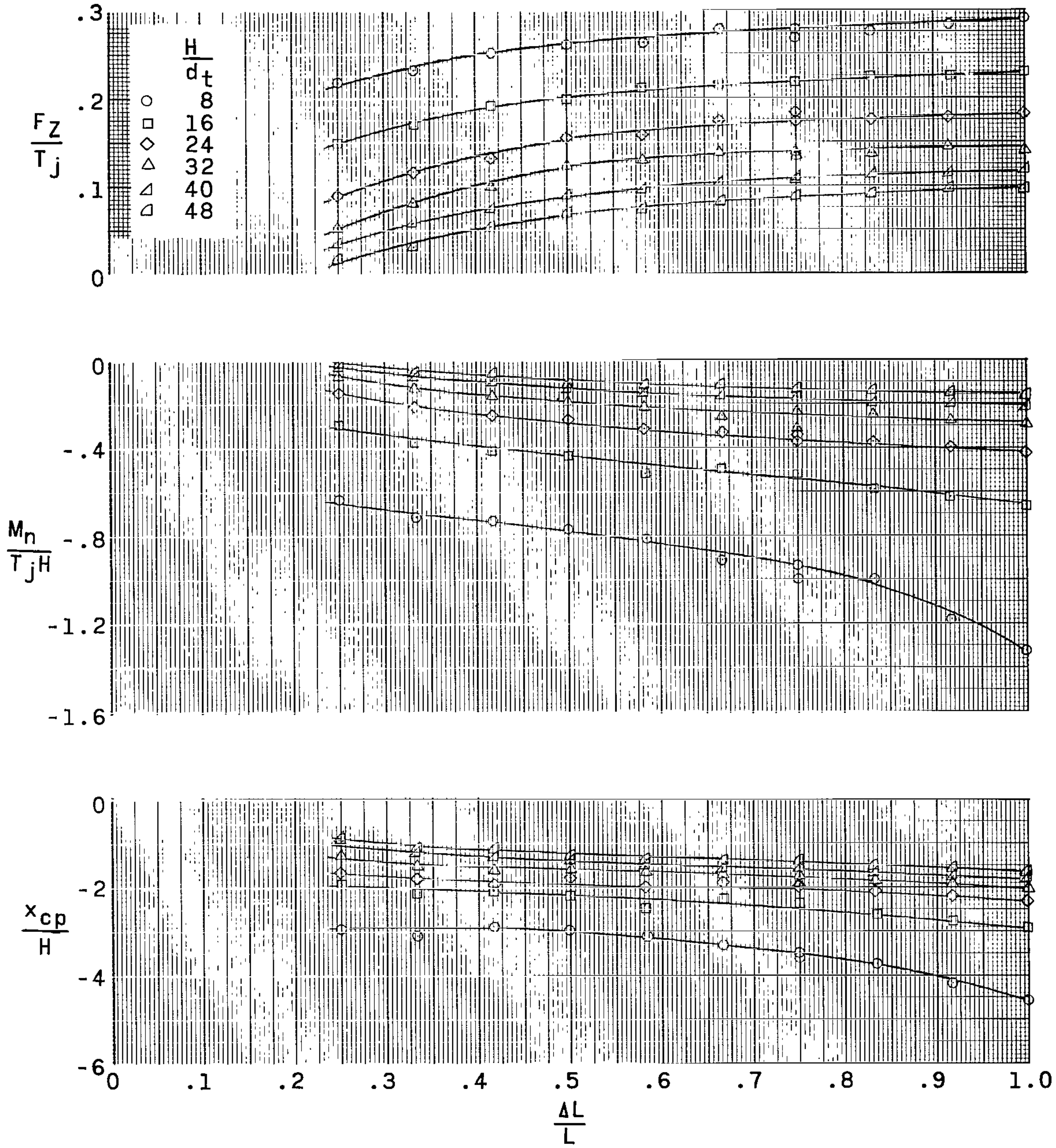


Figure 4.- Typical oscillograph record. Test at Mach number 3.0, $\Delta L/L = 1.0$, $H/d_t = 16$, and $W/L = 1.0$.



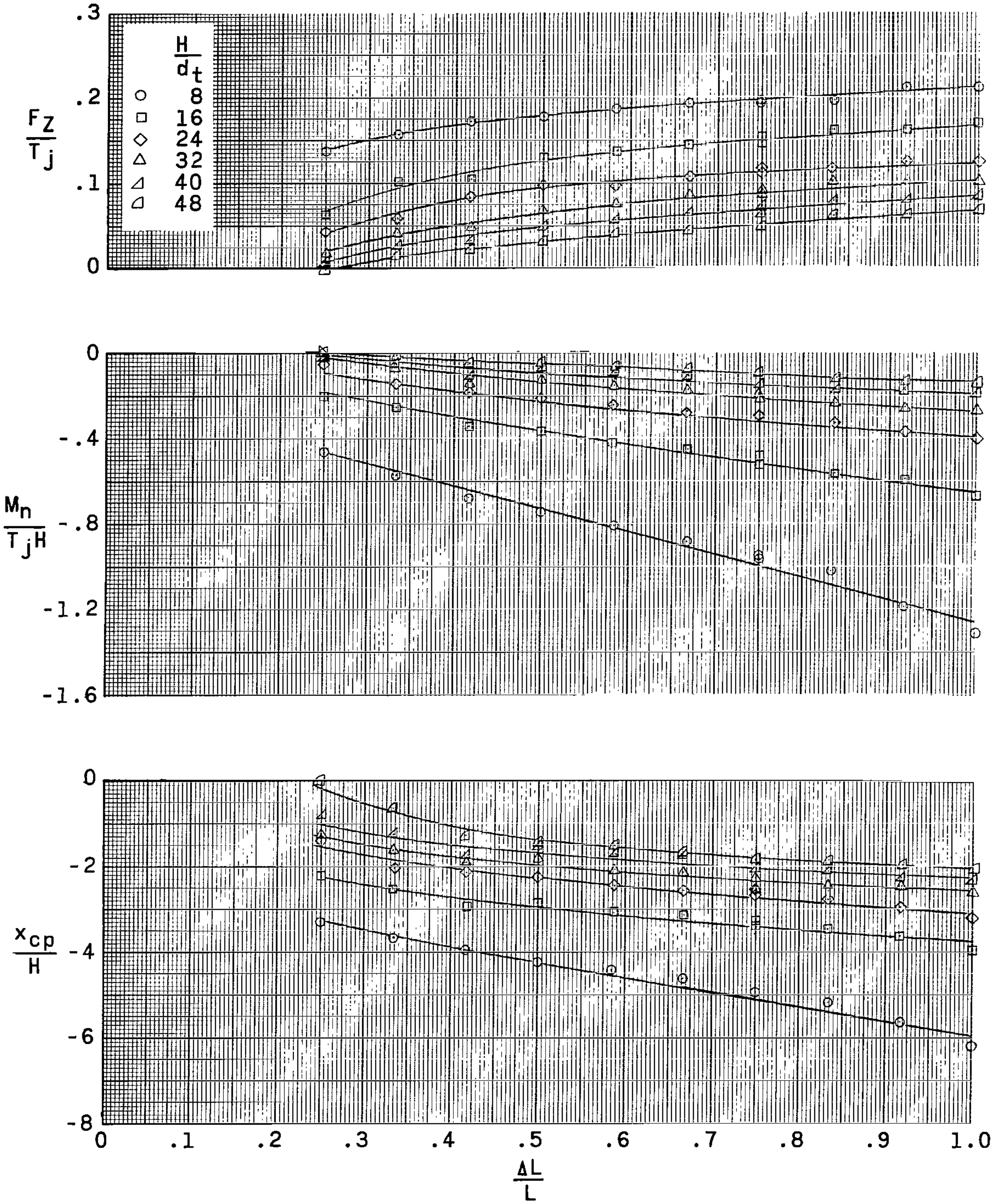
(a) Mach number 1.0 nozzle.

Figure 5.- Variations of normal-force, moment, and center-of-pressure data with longitudinal nozzle location for the plate having a width-length ratio of 0.25 and for various vertical displacements of the nozzles.



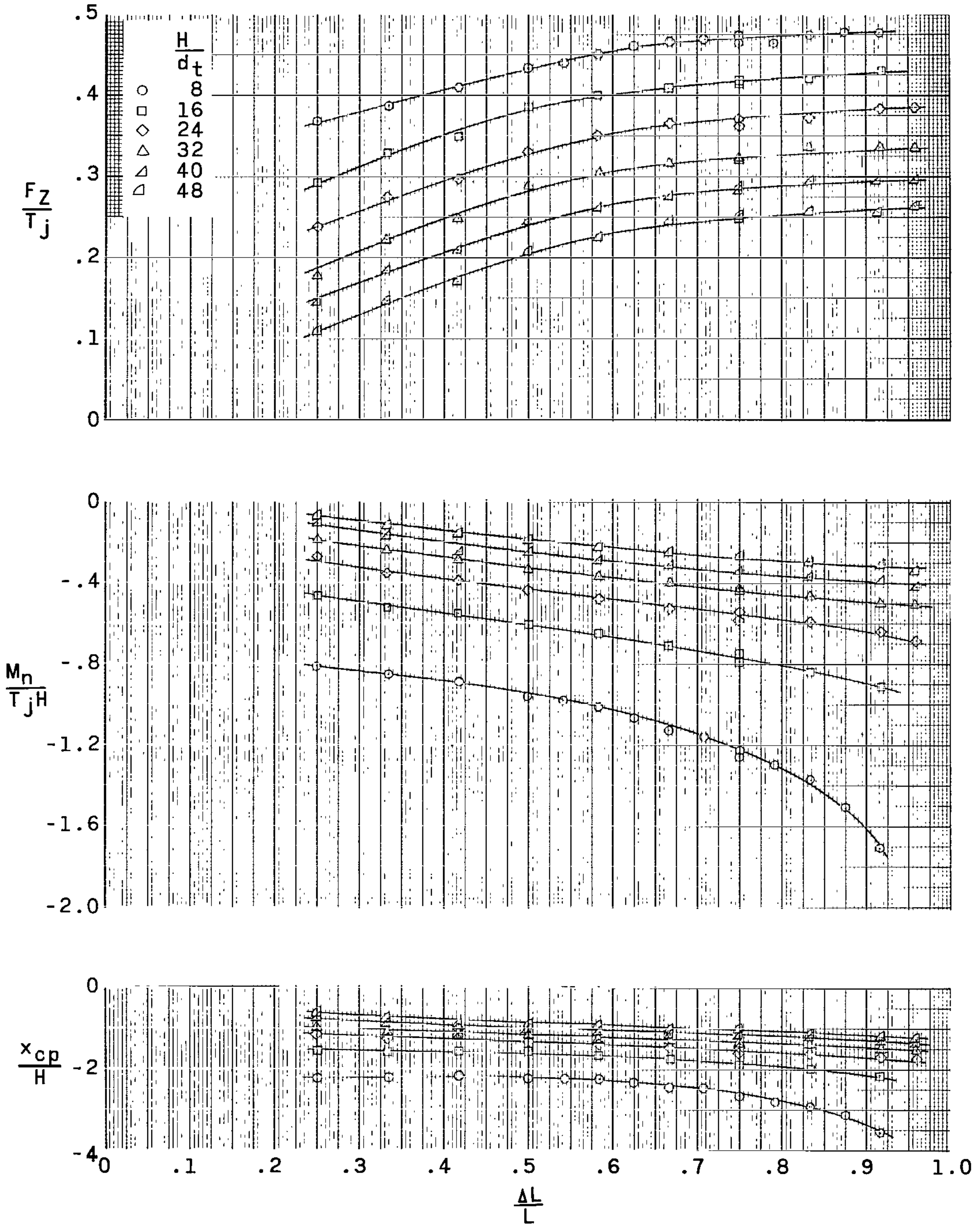
(b) Mach number 3.0 nozzle.

Figure 5.- Continued.



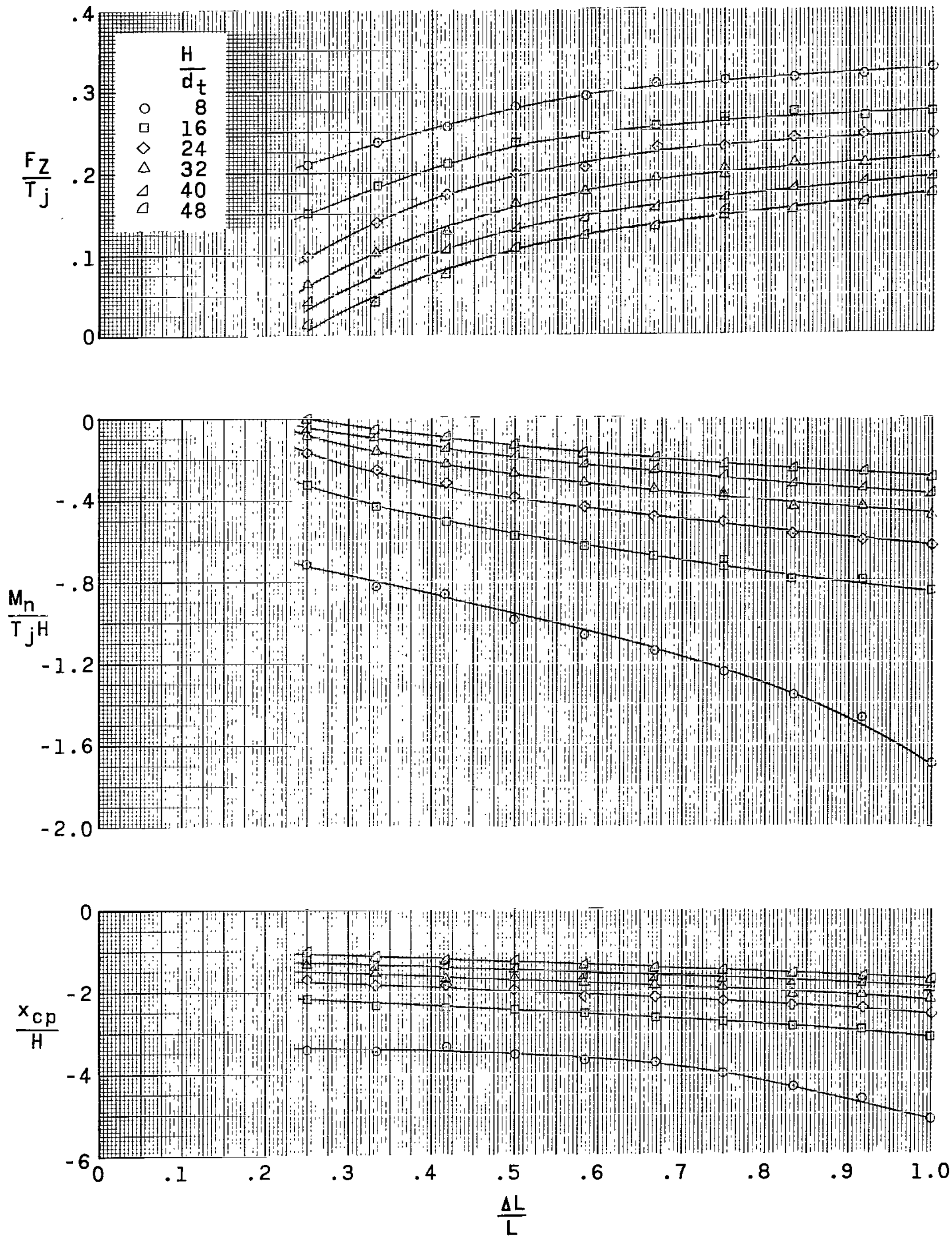
(c) Mach number 5.0 nozzle.

Figure 5.- Concluded.



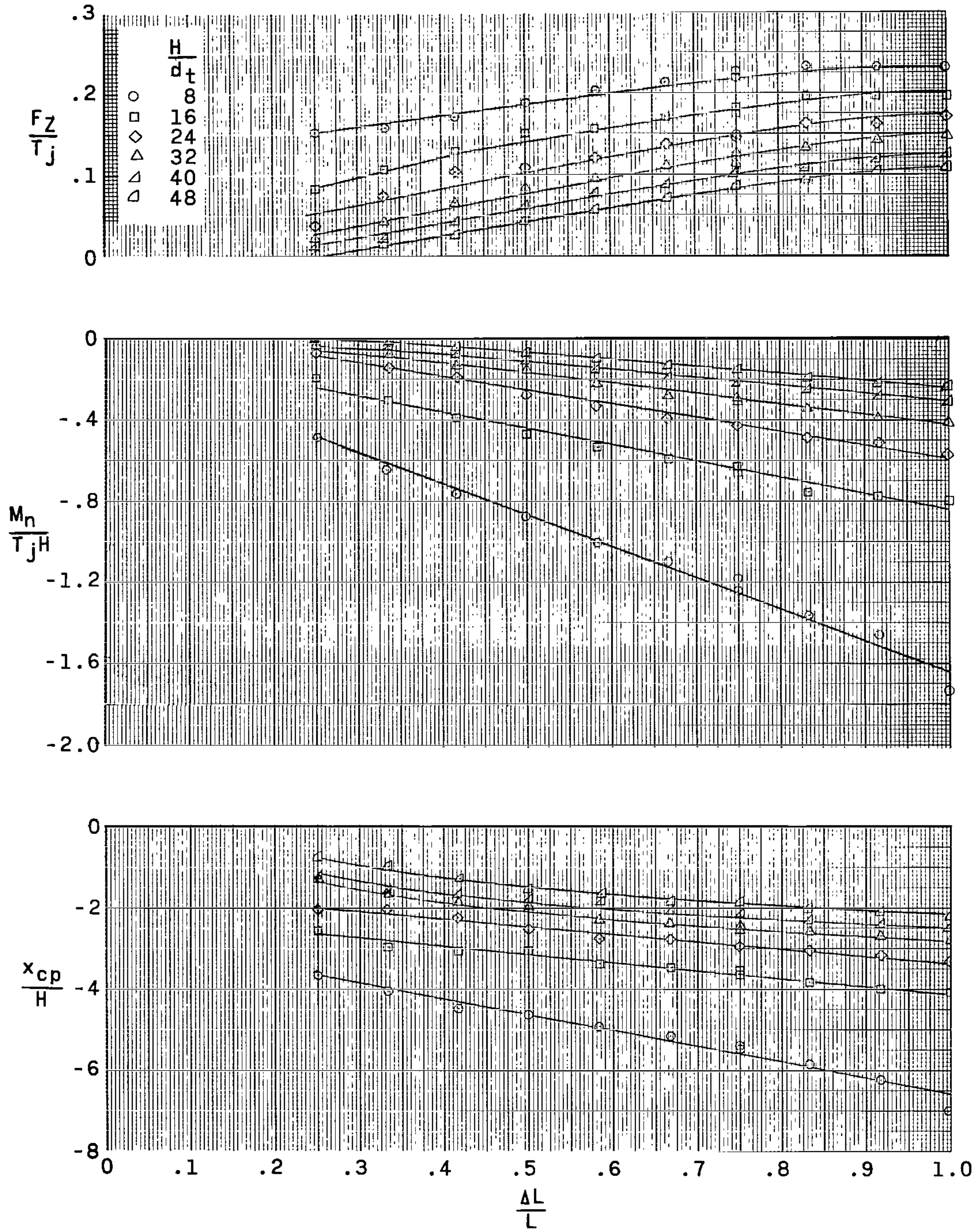
(a) Mach number 1.0 nozzle.

Figure 6.- Variations of normal-force, moment, and center-of-pressure data with longitudinal nozzle location for the plate having a width-length ratio of 0.50 and for various vertical displacements of the nozzles.



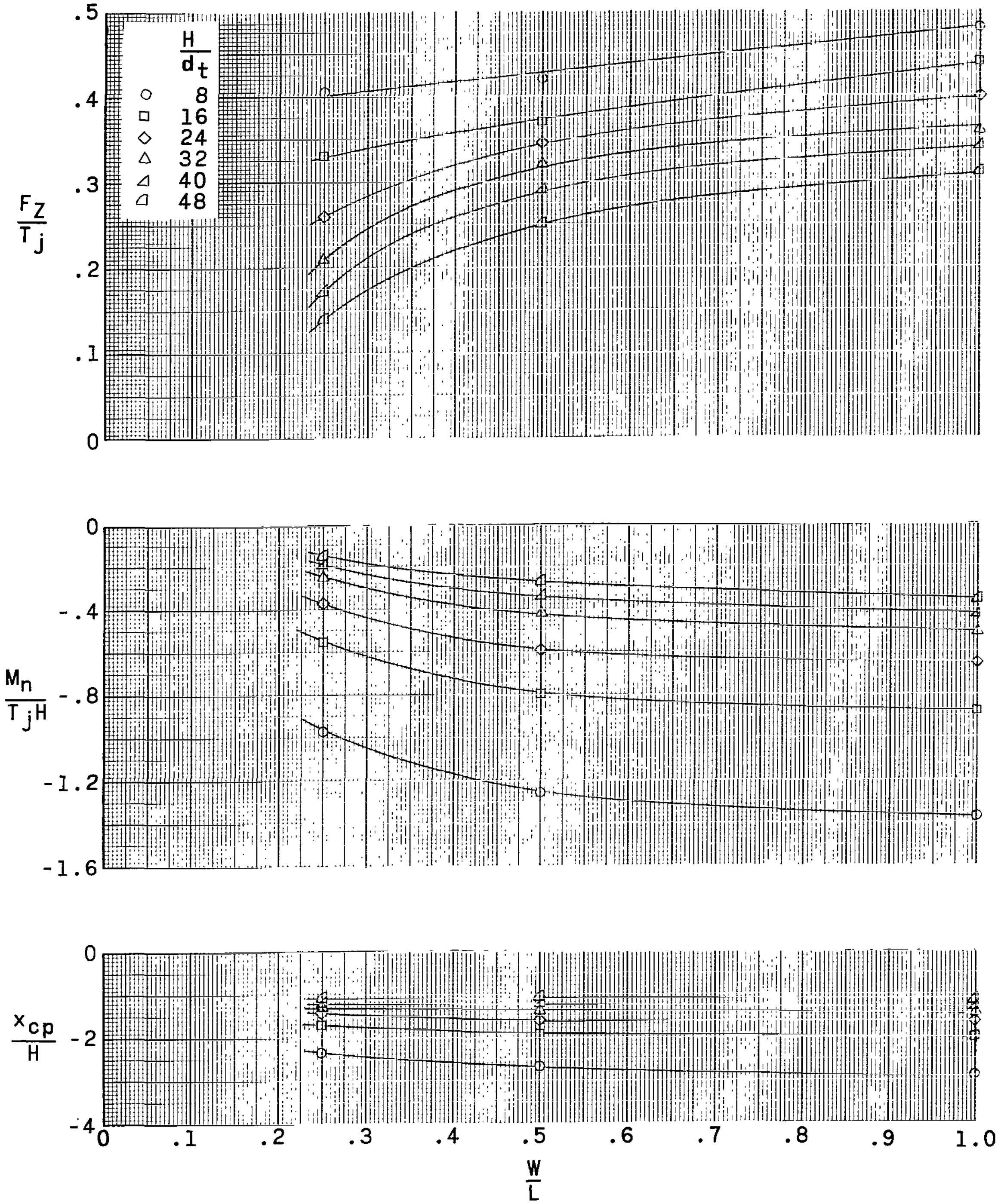
(b) Mach number 3.0 nozzle.

Figure 6.- Continued.



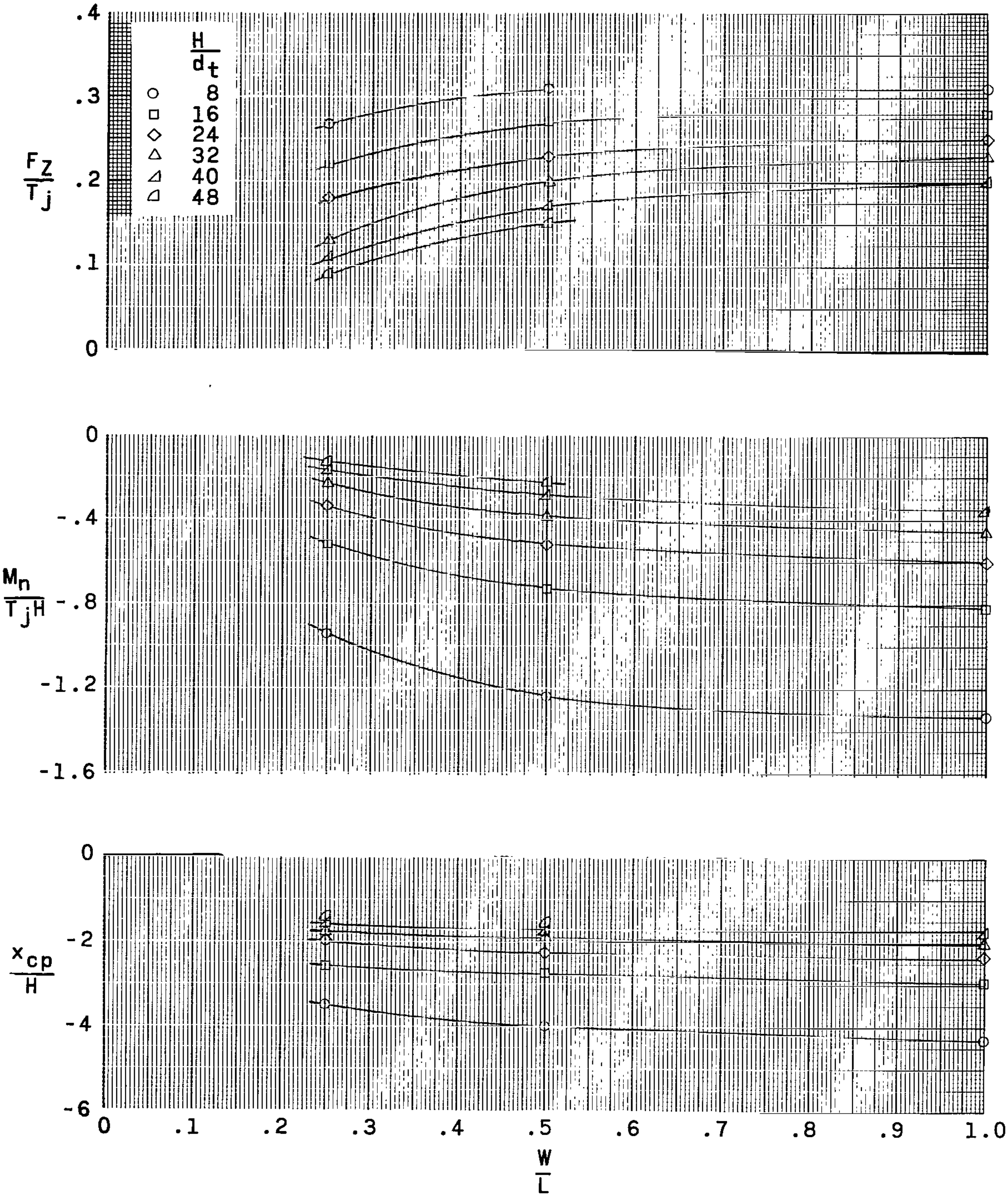
(c) Mach number 5.0 nozzle.

Figure 6.- Concluded.



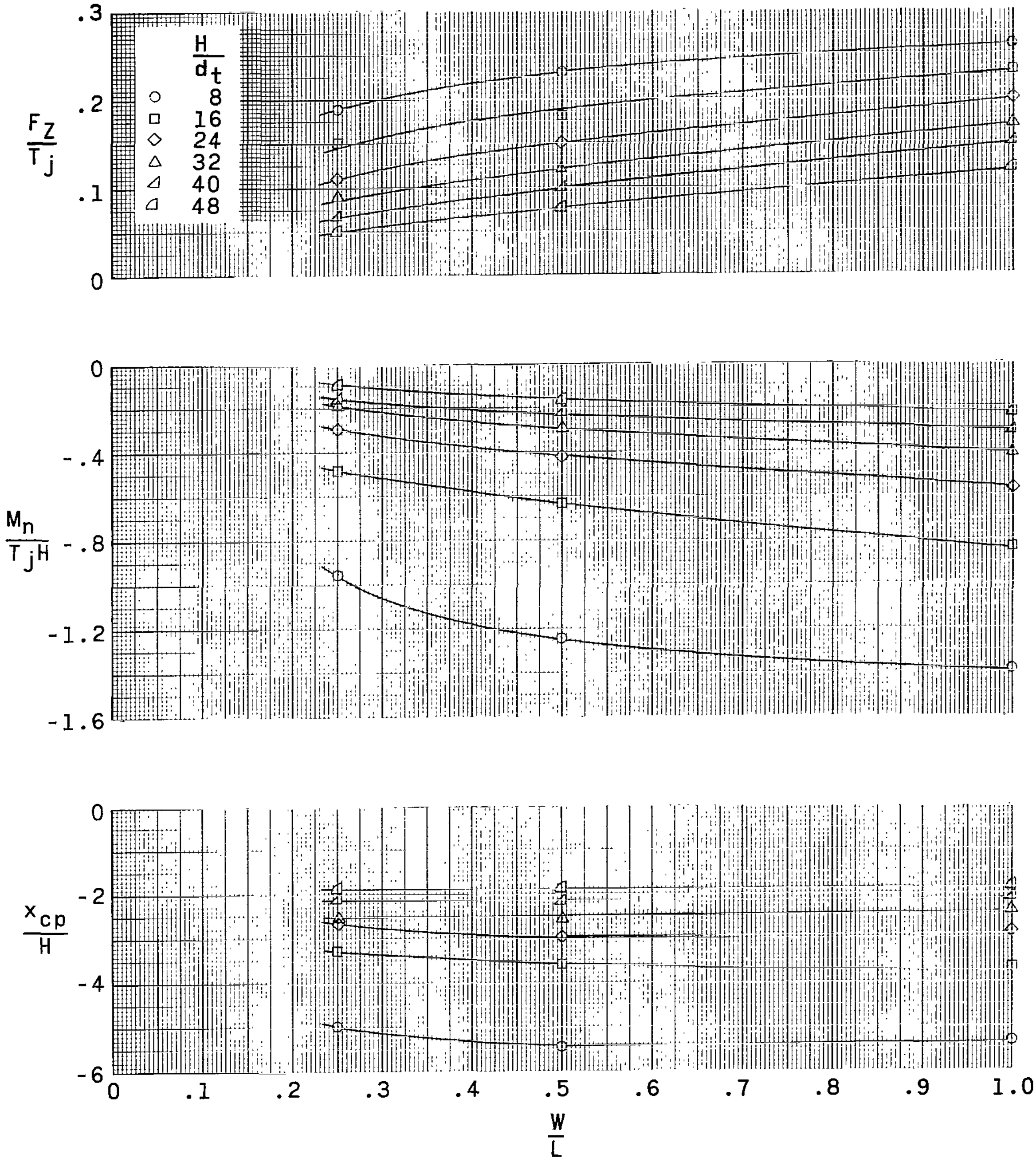
(a) Mach number 1.0 nozzle.

Figure 7.- Comparisons of the normal-force, moment, and center-of-pressure data for three flat-plate widths at a constant longitudinal nozzle location of $\Delta L/L = 0.75$.



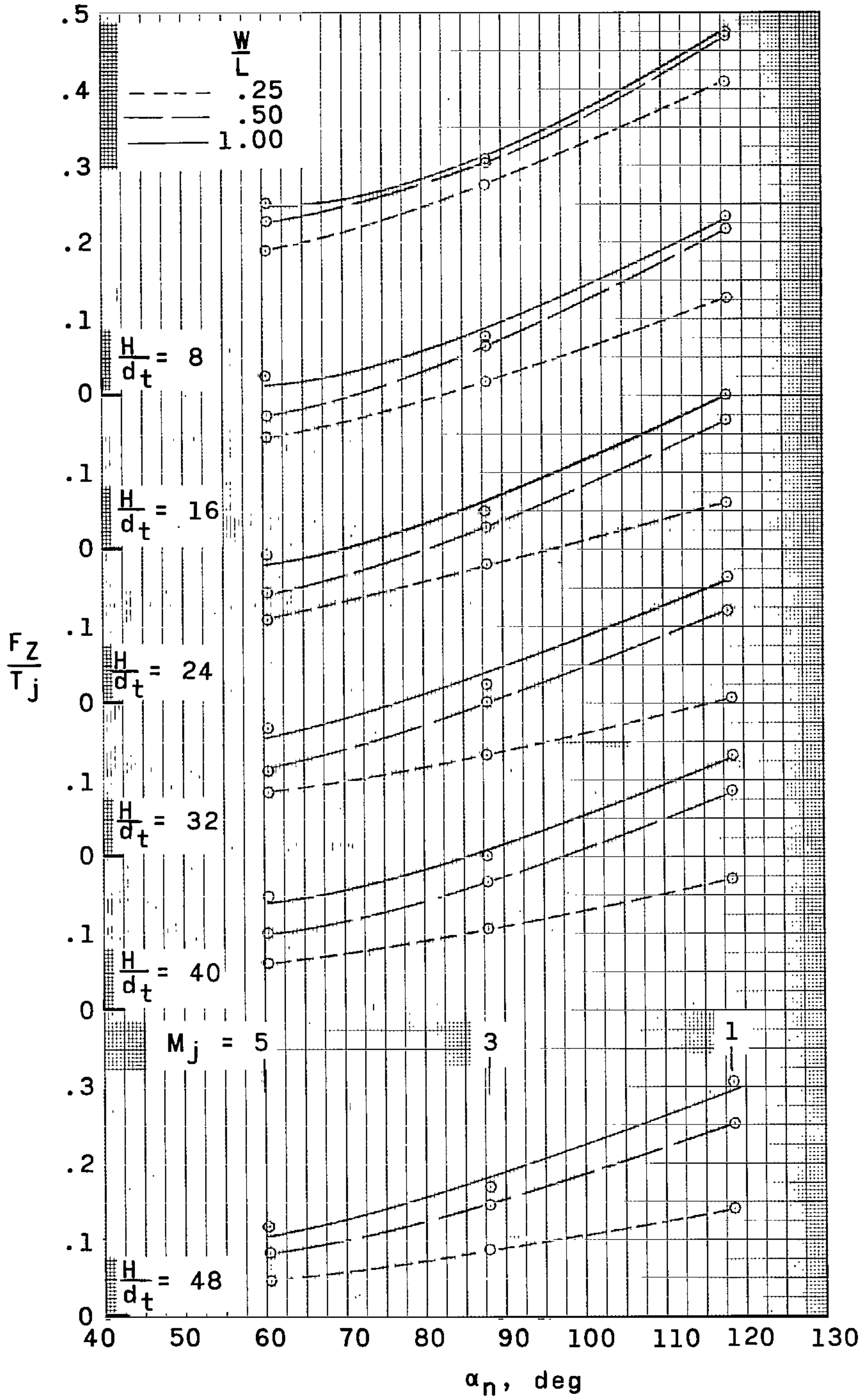
(b) Mach number 3.0 nozzle.

Figure 7.- Continued.



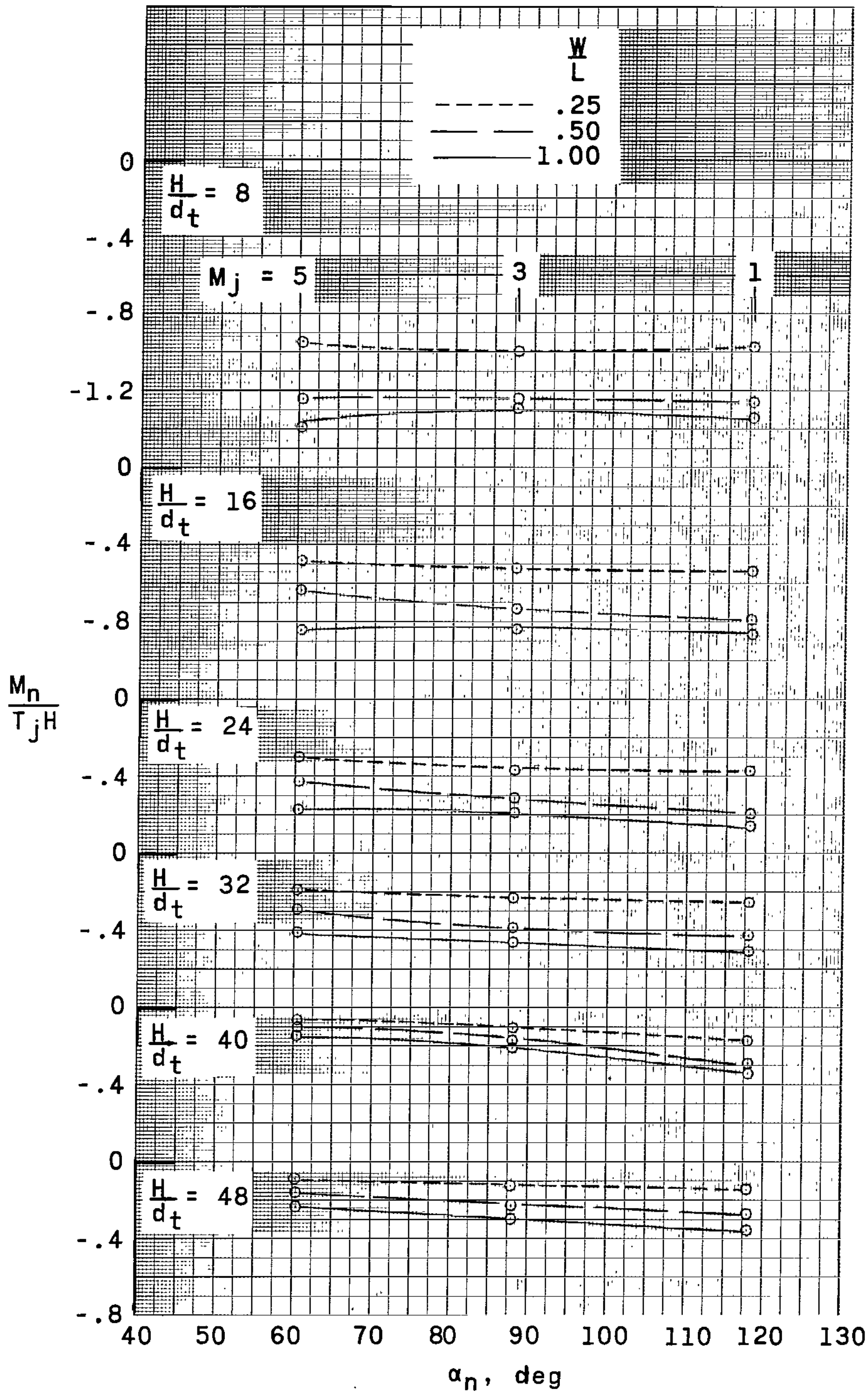
(c) Mach number 5.0 nozzle.

Figure 7.- Concluded.



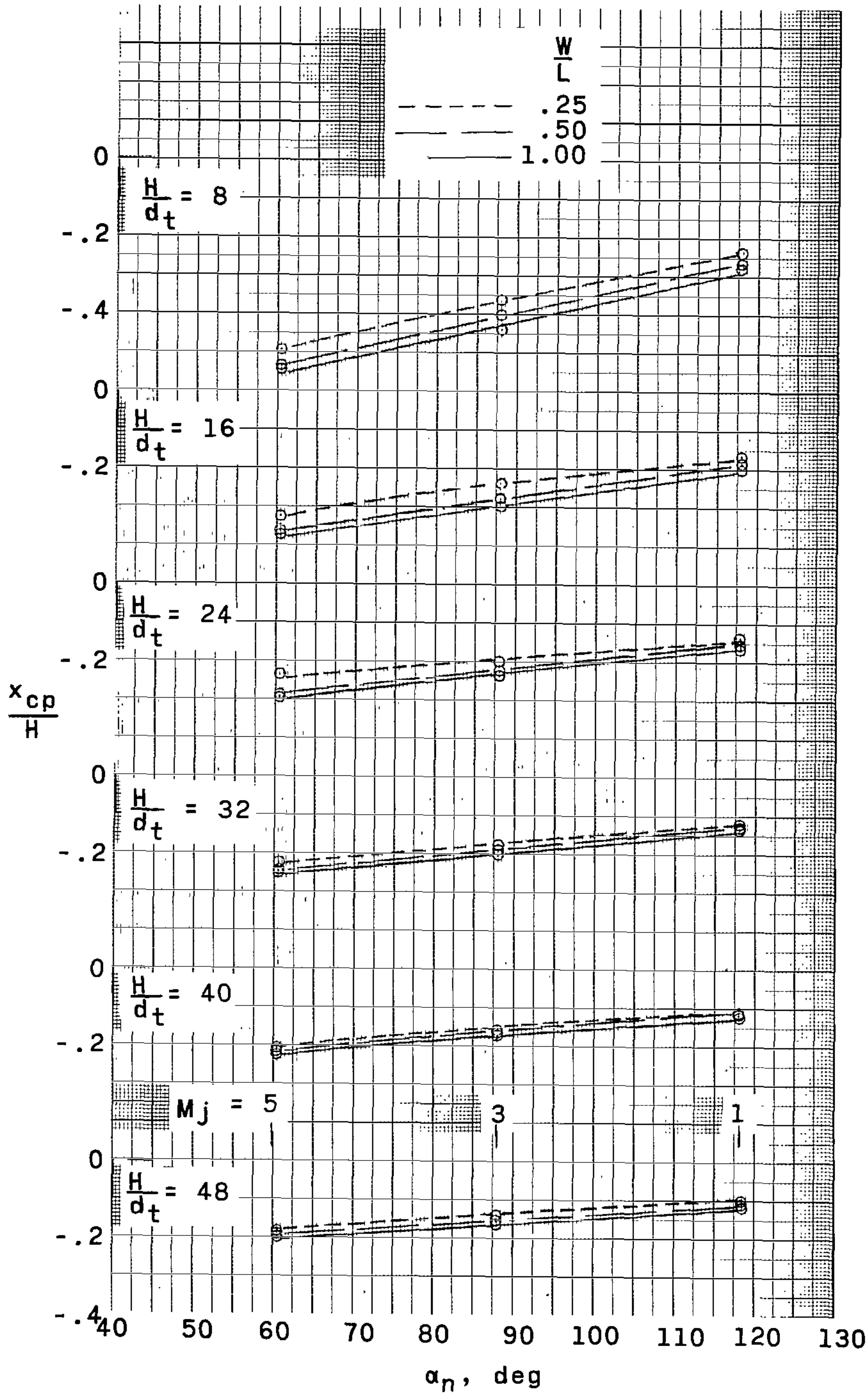
(a) Normal force.

Figure 8.- Variations of normal-force, moment, and center-of-pressure data with initial jet turning angle for nozzles at $\Delta L/L = 0.75$.



(b) Moment.

Figure 8.- Continued.



(c) Center of pressure.

Figure 8.- Concluded.

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